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The Combined Presentation of Deterministic and Stochastic Approaches in the Algorithm of Calculation of Energy Losses in Electric Networks

Alexey A. Gerasimenko* and Evgeny V. Puzyrev
Siberian Federal University
79 Svobodny, Krasnoyarsk, 660041, Russia

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A brief description of deterministic and probabilistic-statistical methods for calculation of electricity losses in the distribution networks of 6–35 kW. The optimal combination of weight deterministic and probabilistic and statistical approaches in the combined calculation of power losses by criterion of a minimum of errors.

Keywords: power losses, multimode, deterministic and stochastic methods, optimal combination.

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Комбинированное представление детерминированного и стохастического подходов в алгоритме расчёта потерь электроэнергии в электрических сетях

А.А. Герасименко, Е.В. Пузырев
Сибирский федеральный университет
Россия, 660041, Красноярск, пр. Свободный, 79

Представлена краткая характеристика детерминированного и вероятностно-статистического методов расчёта потерь электроэнергии (ЭЭ) в распределительных электрических сетях 6–35 кВ. Определено оптимальное сочетание веса детерминированного и вероятностно-статистического подходов при комбинированном расчёте потерь ЭЭ по критерию минимума ошибки.

Ключевые слова: потери электроэнергии, многорежимность, детерминированный и стохастический методы, оптимальное сочетание.

* Corresponding author E-mail address: jane2387@mail.ru

Introduction

Application of the principles of the combined association of deterministic and stochastic methods became a defining trend for constructing algorithms for calculating power loss with high precision and the desired confidence level [1-3]. Determination of power losses with high reliability (accuracy and reliability) it is necessary to solve a number of problems of operation, reconstruction and optimization of power distribution networks.

Electricity losses – the value of monthly reporting as a measure of evaluating the quality of performance and the technical condition of networks, the basis of justification of tariffs for electricity and valuation losses. Especially important are the requirements for the accuracy and reliability of the determination of power losses in assessing the effectiveness of interventions aimed at reducing losses, the solution of optimization problems in a production staged by the criterion of minimum electric energy losses [4, 5].

Combined approach in the determination of power losses

The most effective and common methods of calculating power losses are based on the use of averages (mathematical expectations) load, defined capacity:

$$P_{aver} = \frac{1}{T}\int_0^T P(t)dt = \frac{W_p}{T}; \qquad Q_{aver} = \frac{1}{T}\int_0^T Q(t)dt = \frac{W_Q}{T} \tag{1}$$

or currents

$$I_{aver} = \frac{\sqrt{P_{aver}^2 + Q_{aver}^2}}{\sqrt{3}U} = \frac{\sqrt{W_P^2 + W_Q^2}}{\sqrt{3}U \cdot T}. \tag{2}$$

The last in the map any workload at any arbitrary point in time are the most accurate and reliable integrated parameters of electric modes, taking into account compact point the whole set of modes (multimode) for a given time interval *T*.

For circuit electrical distribution system with m longitudinal sections of the load losses of electricity in general are determined by the exact summation (direct integration) of active power losses on all set of modes of analyzed time period *T* (day, month, quarter, year) according to the expression:

$$\Delta W = \sum_{j=1}^{m}\int_0^T \Delta P_j(t)dt = \sum_{ij}^{n+1}\int_0^T \Delta P_{ij}(t)dt = M\Delta W + \sigma\Delta W \,, \tag{3}$$

where ΔPij – loss of power at site i-j.

$$\Delta P_{ij} = \left[U_i^2 + U_j^2 - 2U_iU_j \cdot \cos(\delta_i - \delta_j)\right] \cdot g_{ij}\,.$$

Under the aforementioned write the expression for energy loss as the sum of the main component $M\Delta W$, determined by average load and variance $\sigma\Delta W$ component reflecting the deviation of loads from the average values.

The main component $M\Delta W$ of energy loss is determined by the result of calculation of the established regime for medium loads (1), (2) with high reliability. The greatest difficulty is the complete and simple account of multimodal in the calculation of variance component that is the determining factor in the calculation of energy losses in general.

Given the deterministic and random parameters of the networks most natural account of multimodal by combining deterministic and probabilistic and statistical methods into a single combined algorithm of calculation of power losses [1-3] that in the greatest measure allows to consider the properties and use possibilities and advantages of combining algorithms. Thus it is necessary to allocate two directions of this Association.

The first direction of the combined method of determining electricity losses in distribution networks is the direct mutual addition of deterministic-stochastic approaches and the model balancing the primary and the dispersion component of energy losses [2, 3]. A deterministic algorithm for calculating the technical component of losses, based on the operation data systems head of accounting and using the information on the composition, configuration and circuit parameters, is implemented in the form:

$$\Delta W = 3k_f^2 \sum_{j=1}^{m} I_{aver\,j}^2 R_j T = \left[\sum_{j=1}^{m} \Delta P_{aver\,j} + (k_f^2 - 1)\Delta P_{aver} \right] T = M\Delta W + \sigma\Delta W \,, \tag{4}$$

known as the method of medium loads, where the multimodal information is taken into account using the shape factor:

$$k_f = \frac{\sqrt{d}}{W_P + W_Q} \left(\sqrt{\sum_{i=1}^{d} W_{Pi}^2 + \sum_{i=1}^{d} W_{Qi}^2} \right), \tag{5}$$

and the equivalent voltage source is a power center electrical distribution system:

$$U_{eq} = \sqrt{0{,}9U_{\max}^2 + 0{,}1U_{\min}^2} \,, \tag{6}$$

which calculates base established regime at the average loads and cumulative power losses in the elements of the electrical distribution system. If the average value of the coefficient k_f, defined by d daily measurements of the released electric power W_P and W_Q in the network are not taken into account the individual characteristics of the mode of power consumption of different network fragments, which leads to additional error. The unification of the deterministic method into a single algorithm with stochastic allows to compensate for the lack.

Stochastic method of calculating the power losses is based on the factor model of electrical loads. The theoretical foundations of such modeling, a statistical model of the established regimes and the practical implementation of the corresponding probabilistic-statistical apparatus in the problem of determining the integral characteristics of the modes are presented in [6-11].

The account of the multimodal network is performed using the correlation moment matrix, is a compact statistical model which is obtained based on the method of principal component is a private implementation of factor analysis [9-11].

The result of component analysis of statistically representative training sample n load curves for various distribution networks obtained orthogonal to the main factors – generalized model graphs corresponding to each of the found eigenvectors of the matrix of correlation moments:

$$\Gamma_j = \sum_{i=1}^{n} \upsilon_{ki}^{/} P_{ij} + \sum_{i=1}^{n} \upsilon_{ki}^{//} Q_{ij}, \; j = \overline{1,d} \,, \tag{7}$$

Where $\upsilon^{/}_{ki}, \upsilon^{//}_{ki}$ are components of the k-th factor of the display (eigenvectors $\bar{\upsilon}_k$ of the correlation moment matrix) of the source aggregate load curves with d-intervals of constancy.

The original daily, monthly, or another time interval *T* graphics load and generator nodes P_{ij}, Q_{ij} is represented by the mathematical expectation of the load MP_i, MQ_i and modelled deviations from the mathematical expectations of the load in the form of a linear combination of K statistically steady main factors:

$$P_{ij} = MP_i + \sum_{k=1}^{K} \upsilon^{/}_{ki} \Gamma_{kj}; \quad Q_{ij} = MQ_i + \sum_{k=1}^{K} \upsilon^{//}_{ki} \Gamma_{kj}, \quad j = \overline{1,d}, \tag{8}$$

This representation of loads has been effective since retrieving (7) acceptable accuracy enough for up to three or four (K<<n) orthogonal graphs corresponding to the largest eigenvalues of the matrix of correlation moments and reflect 80-90 % of the total variance of the initial load [7-11]. The analyzed parameters V_i, δ_i as P_i, Q_i are represented as linear combinations of orthogonal graphs:

$$V_{ij} = MV_i + \sum_{k=1}^{K} \gamma^{//}_{ki} \Gamma_{kj}; \quad \delta_{ij} = M\delta_i + \sum_{k=1}^{K} \gamma^{/}_{ki} \Gamma_{kj}, \quad j = \overline{1,d}, \tag{9}$$

Where the coefficients $\gamma^{/}_{ki}, \gamma^{//}_{ki}$ are determined from the solution of the linearized at the point MP_i, MQ_i of a system of linear equations.

$$\begin{aligned} &\sum_{j=1}^{n} \frac{\partial P_i}{\partial \delta_j} \gamma^{/}_{kj} + \sum_{j=1}^{n} \frac{\partial P_i}{\partial V_j} \gamma^{//}_{kj} = \upsilon^{/}_{ki} \quad i = \overline{1,n}; \\ &\sum_{j=1}^{n} \frac{\partial Q_i}{\partial \delta_j} \gamma^{/}_{kj} + \sum_{j=1}^{n} \frac{\partial Q_i}{\partial V_j} \gamma^{//}_{kj} = \upsilon^{//}_{ki} \quad i = \overline{1,n}, \quad k = \overline{1,K}. \end{aligned} \tag{10}$$

Simulation (7)÷(10) allows to obtain expressions for the correlation moments of the analyzed variables:

$$k(V_i V_j) = \sum_{k=1}^{K} \gamma^{//}_{ki} \gamma^{//}_{kj}; \quad k(V_i \delta_j) = \sum_{k=1}^{K} \gamma^{//}_{ki} \gamma^{/}_{kj}; \quad k(\delta_i \delta_j) = \sum_{k=1}^{K} \gamma^{/}_{ki} \gamma^{/}_{kj}; \quad i,j = \overline{1,n}. \tag{11}$$

Expanding the function (3) in a Taylor series in small the area of mathematical expectations of performance parameters, and then executing integration operation is based on a statistical model of the established regimes of (7)÷(11), the expression for power loss evaluation of probabilistic-statistical method we write in the form:

$$\begin{aligned} \Delta W = M\Delta W + \sigma \Delta W \approx \left[\Delta P(M\,\bar{V}, M\,\bar{\delta}) \right] \cdot T + \\ + \left[\frac{1}{2} \sum_k \sum_i \sum_j \gamma^{/}_{ki} \gamma^{/}_{kj} \frac{\partial^2 \Delta P_{ij}}{\partial \delta_i \partial \delta_j} + \sum_k \sum_i \sum_j \gamma^{/}_{ki} \gamma^{//}_{kj} \frac{\partial^2 \Delta P_{ij}}{\partial \delta_i \partial V_j} + \frac{1}{2} \sum_k \sum_i \sum_j \gamma^{//}_{ki} \gamma^{//}_{kj} \frac{\partial^2 \Delta P_{ij}}{\partial V_i \partial V_j} \right] \cdot T. \end{aligned} \tag{12}$$

Calculation of electricity losses is based on a calculation of the established regime and K of solutions of systems of linear equations (10).

In light of the definition of the main component of the power losses at medium loads $M\Delta W$ (4) and variance $\sigma\Delta W$ based stochastic approach (12) and comparing expressions (4) and (12) specifies the shape factor:

$$k_f^2 = 1 + \frac{\sigma \Delta W}{M \Delta W}, \tag{13}$$

briefly considering using $\sigma\Delta W$ the deviation of loads from the average values of the whole scheme. Recalculation according to the formula (13) allows to reduce the smoothing effect of a uniform shape factor k_f, as defined in the deterministic method (4) according to the head of area and take into account the multimode branched part of the network.

Subsequent adjustments to the loss ΔW on the expression (4) W supplied to the network of electricity (pass of the head area minus losses) and medium (pseudoregma) load nodes in the distribution networks allows alternately specify the basic and dispersion components of energy losses in (4) and (12) respectively. According to this iterative procedure, the values ΔW of the total energy losses, identified by both algorithms (4) and (12) are balanced to the same value, as a rule, the results of two or three approximations [2, 3].

The proposed combined method allows to reduce the component of error arising from the spread of the influence calculated according to (5), (6) only the main part k_f of the whole scheme. The accuracy of the calculation of the technical (load) power losses for overhead lines in the general case depends on a consideration of the totality of regime and atmospheric conditions.

Effect on power losses in overhead lines (through parameters $R(t_p)$ is a function of the temperature of the wire) intramonth changes of regime-atmospheric factors (air temperature, speed and wind direction, solar radiation, etc.) and electrical energy consumption is taken into account in terms of losses (4).

$$\Delta W = 3k_{aver.month} \cdot k_f^2 \sum_{j=1}^{m} I_{aver\,j}^2 \cdot R_j(t_p) \cdot T = k_{aver.month} + \sum_{j=1}^{m} \Delta P_{aver} \cdot k_f^2 \cdot T \tag{14}$$

using the correction factor [12-14]. Minimization of error is achieved by dynamic amendments depending on the structure and network utilization [14, 15]. The total error of calculation of electricity losses in the network is characterized with reliability of 0.95 the average value (close to zero) in the interval from -0,05 to -0,09 % and the greatest variation from -2.5 to 1.5 %.

Another implementation of the combined approach (algorithm) associated with the direct use of the results of deterministic $\Delta W_{\det}$ (4) and stochastic ΔW_{stoch} (12) calculation methods of electric energy losses in the composition of the weighted average value [1].

$$\Delta W_{estim} = \Delta W_{\det} \cdot \eta + \Delta W_{stoch} \cdot \alpha \,, \tag{15}$$

where α, η is the best (optimal) values of the weights that are associated with ratios $\eta = 1 - \alpha$ that determine the weight (part) of the result of each algorithm in the calculation of the weighted average value of losses of electricity (16).

$$\Delta W_{estim} = \Delta W_{\det} \cdot (1 - \alpha) + \Delta W_{stoch} \cdot \alpha \tag{16}$$

are determined by statistical tests on a representative sample of N schemes of distribution networks. The optimality criterion of the composition of the weighted average value adopted low average linear deviation (relative error):

$$\delta\Delta W_{estim}(\alpha) = \frac{1}{N}\sum_{i=1}^{N}\frac{\Delta W_{estim\ i}(\alpha) - \Delta W_{refer\,i}}{\Delta W_{refer\,i}} \cdot 100\% \qquad (17)$$

where the estimated value $\Delta W_{estim\ i}(\alpha)$ of losses in the i-th diagram are calculated for the weights of a stochastic variable with the result of this step, for example, equal to 0,1 and with decreasing order of magnitude around the minimum of function (17); $\Delta W_{refer\,i}$ is the reference value of the power losses in the i-th scheme with m-branches

$$\Delta W_{refer} = \sum_{j=1}^{m}\int_{0}^{T}\Delta P_j(t)dt \approx \sum_{j=1}^{d}\Delta P_{\Sigma j} \cdot t_j \qquad (18)$$

is determined by the results cyclically performed d-calculation of the established regimes, each of which calculated total value of power losses $\Delta P_{\Sigma j}$ in the network for the interval j of graphs nodal loads.

The change in the average selective value of the relative error for various combinations of deterministic and probabilistic-statistical results of calculation of energy losses for a statistically representative set of schemes of distribution grids presented in the appendix.

App

Determination of the optimal weight (ratio) of the results of deterministic and stochastic algorithms for calculation of power losses by the combined method. Optimal according to criterion (17) the ratio determined for the sample of 20 schemes of electric networks with voltage of 35/10 kV, one of which is shown in Fig. 1.

The network, built on a radial type, made of the same wire aluminum-steel 70/11 full resistance $\bar{z}_0 = 0{,}43 + j0{,}35$ Ohm/km. Parameters of transformers are given in Table. 1.

A power consumption regime determined branch daily charts (Fig. 2.) is approximated using a d=12 intervals of constancy (Table. 2).

The load is set at nodes 3 and 7, graphs a) with $\bar{S}_3 = 4000\ MBA$ and $\bar{S}_7 = 1600\ MBA$, the nodes 4 and 6 – graphs b) and c) respectively with $\bar{S}_4 = \bar{S}_6 = 6300\ MBA$. The voltage at the source

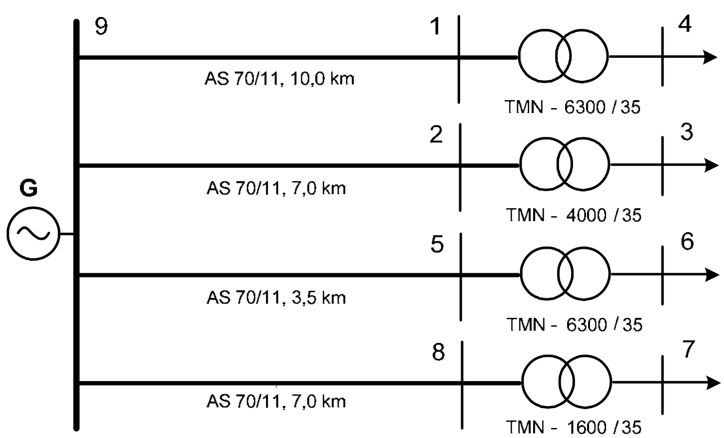

Fig. 1. Diagram of the electrical network 35/10 kV

Table 1. The parameters of transformers of electric networks

The section of the network	Type transformer (oil transformer regulation under load) (In Russian)	$U_{ном}$, kV		R_T, Ω	X_T, Ω	G_T, µS	B_T, µS
1–4	TMN-6300/35	35	11	1,40	14,6	7,51	46,29
2–3	TMN-4000/35	35	11	2,60	23,0	5,47	32,65
5–6	TMN-6300/35	35	11	1,40	14,6	7,51	46,29
8–7	TMN-1600/35	35	11	12,4	49,2	4,16	22,45

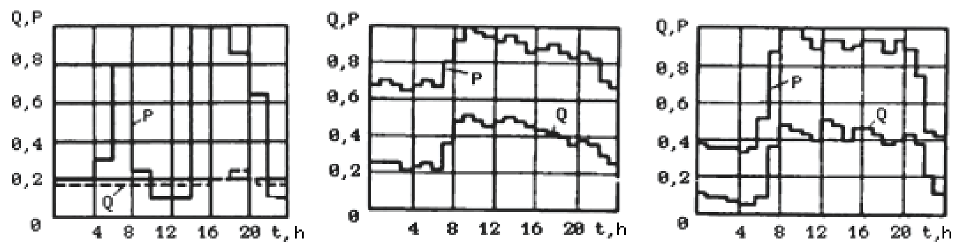

Fig. 2. Sectoral schedules of electric loadings: a) lighting in residential buildings; b) the food industry; c) light industry

Table 2. Estimated graphs electrical loads (in relative units)

The types of schedules of electric loadings		0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24
a	P	0,20	0,20	0,30	0,80	0,25	0,10	0,10	1,0	1,0	0,85	0,65	0,10
	Q	0,18	0,18	0,18	0,18	0,18	0,18	0,18	0,18	0,20	0,25	0,18	0,18
b	P	0,70	0,68	0,70	0,80	1,0	0,98	0,95	0,90	0,90	0,85	0,82	0,70
	Q	0,25	0,25	0,24	0,37	0,50	0,48	0,50	0,48	0,41	0,35	0,38	0,30
c	P	0,38	0,35	0,35	0,70	1,0	0,90	0,93	0,90	0,92	0,90	0,80	0,45
	Q	0,10	0,09	0,08	0,26	0,50	0,40	0,50	0,45	0,43	0,40	0,30	0,15

of supply for d daily periods is taken to change in accordance with the principle of counter-regulation.

In accordance with a change in loads as a result d calculations of the established regimes to calculate the power consumption in the n network nodes

$$W_P = \sum_{i=1}^{d} P_i\, t_i; \quad W_Q = \sum_{i=1}^{d} Q_i\, t_i, \quad i = \overline{1,n}, \tag{19}$$

Reference values ΔW_{refer} of energy losses (18) and released to the network of electricity

$$Э_{omnP} = \sum_{j=1}^{d} P_j^{\Gamma} t_j ; \quad Э_{omnQ} = \sum_{j=1}^{d} Q_j^{\Gamma} t_j , \quad j = \overline{1,n} , \tag{20}$$

where $P_j^{\Gamma}, Q_i^{\Gamma}$ is the flow power head plots of time interval *j*.

On the basis of the thus formed data (5), (6), (20) system head of accounting determined by the value of the power losses in a deterministic method (4), implemented in the industrial program «REG10PVT» [14-16].

Using the energy consumption data (19) and respectively medium loads (1) calculated power losses of the stochastic method (12) through the program «SETI» [8].

For a given sample schemes of distribution grids as a result of comparing the weighted average (combined) electricity losses (15) formed with different combination α of the results of deterministic and stochastic methods, reference values (18) the obtained dependence (Fig. 3) changes in average sample values $\delta_{aver} = \delta\Delta W$ of the relative error (17).

It is the smallest value of δ_{aver} = 0,020 % with the empirical dispersion σ^2 = 8,73, lie in a narrow range of variation sign of the error α = [0,7; 0,8].

Clarification of the minimum value of the function (17) in the interval in increments of α = 0,01 (Fig. 3.) gives minor amendment sample mean error δ_{aver} = 0,019 % and determines the optimal required ratio of α = 0,73 and η = 1 – 0,73 = 0,27 weight results in the national weighted average losses of electricity (16) generated by a probabilistic-statistical and deterministic methods.

Give interval estimates of the average error. Every experience (experiment) is implemented according to the results of calculation of electricity losses deterministic and stochastic methods and the analysis of the resulting weighted average loss in weight α change in the interval from 0 to 1 with

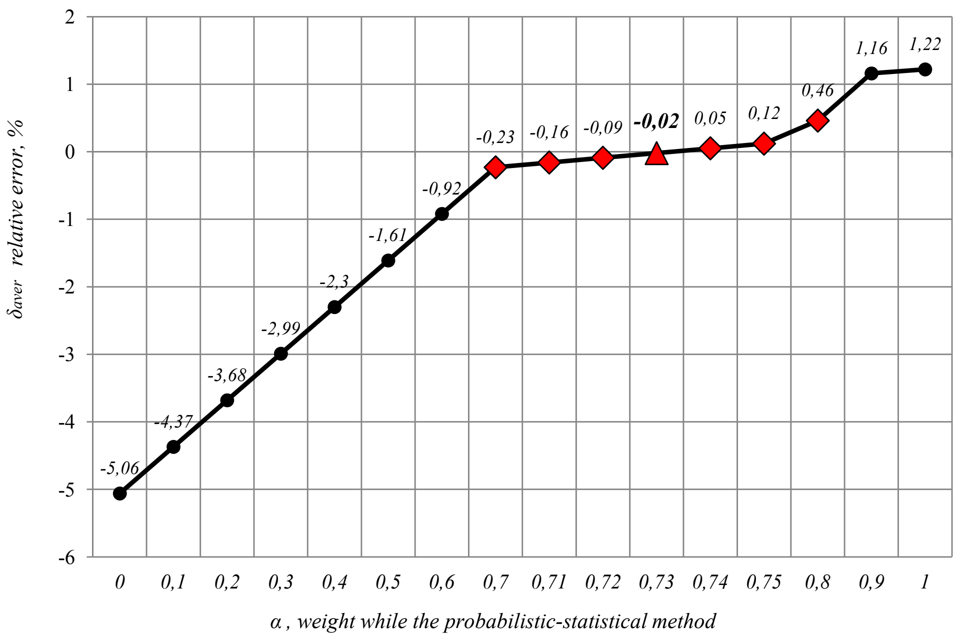

Fig. 3. The change of average sample values of relative error at various combinations of weight of deterministic and probabilistic-statistical methods of calculation of energy losses

a fixed step for each scheme. Volume independent of experiments on random δ (17) is determined by the number of circuits N the sample.

With the reliability $\beta = 0{,}95$ of and the number of degrees of freedom $k = N - 1 = 20 - 1 = 19$ in accordance with the value of the student distribution quantiles is $t_\beta = 2{,}086$ [19]. Then with a precision of $\varepsilon = t_\beta \dfrac{\sigma}{\sqrt{k}} = 2{,}086 \cdot \dfrac{2{,}95}{\sqrt{19}} = 1{,}41$ mathematical expectation of the error of $\delta_{aver} = 0{,}019$ is covered by confidence interval $\Upsilon_\beta = \left(\delta_{aver} - \varepsilon; \delta_{aver} + \varepsilon\right) = (-1{,}38; +1{,}42)$ % and a reliability of 0,95.

Conclusion

The performance of the above combined approaches allows to obtain the estimated value of the loss in electricity with high reliability, that is, with an average error approaching zero and scatter not exceeding the error of the original data. The credibility of the computed value of losses is higher than to the desired parameter ΔW derived from independent use of deterministic or probabilistic-statistical methods.

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